Topology Optimization considering Additive Manufacturing constraints in an industrial context

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Abstract

Manufacturing-oriented Topology Optimization (TO) is an active field of research both in academic and in industrial world. On one hand, the potential offered by topology optimization as a powerful design method is undeniable in improving the structural performance in different areas of engineering. On the other hand, Additive Manufacturing (AM) technology provides numerous industrial mechanisms of manufacturing and producing complex structure where classical methods fail to deliver an outcome.

Merging both branches of TO and AM together introduces encouraging results in terms of designing optimized structures showing an acceptable mechanical response. In our contribution, we present a topology optimization model developed for additive manufacturing design. Using an innovative meshing algorithm, we particularly showed how the topology optimization could be implemented in order to consider the constraints of additive manufacturing specifically the printability of the parts with overhang angle.

The design of the self-supporting structures is a challenging part of the additive manufacturing process, without which the process becomes tedious in terms of time, efficiency and financial resources. Therefore, a continuous effort for a better understanding of such issue is justified. In this paper, we suggest an improvement on the work carried out by Langelaar in this context. The model used in this study is a more complicated geometry compared to

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the model used by Langelaar. While the model used by Langelaar is a simple academic model, our work is based on a complex industrial geometry. The Optimality Criteria (OC) was exploited as the TO method in our work. The novelty of our work lies particularly in utilising the unstructured mesh, which, is a first attempt in using such grids in this context. An innovative numerical algorithm is designed specifically for taking into account the critical overhang design in order to avoid support structures. It is worth mentioning that the numerical results obtained in our research work are the outcome of an in house code developed in collaboration between Altran Technologies and Université de Technologie de Belfort-Montbéliard.

1. Introduction

Additive manufacturing also known as 3D printing has established itself as a form of potentially disruptive manufacturing technique over the recent years. This technique has shown its potential in a variety of industrial domains such as automotive [4, 12], medical engineering [5, 15], aerospace [3, 13] etc. Additive manufacturing process follows a layer by layer build up process which gives an entirely different nature to this technique in comparison to classical methods of fabrication. This manufacturing process overturns the traditional manufacturing method that is the subtractive manufacturing, that makes the fabrication of new and complex geometrical features possible. The different build process offered by additive manufacturing removes the geometry complexity restriction faced in classical methods and eventually the efficiency and cost of fabrication is going to be unaffected by this limitation [8]. This latter characteristic provides an extended manufaturability freedom which makes additive manufacturing a great candidate for exploiting the free-form designs put forward by topology optimization [10].

Topology optimization can be defined as a free-form material distribution scheme that aims at seeking optimal material distribution for obtaining enhanced mechanical or multi-physics performances. However, one of the main challenges of topology optimization nowadays is the manufacturability of the obtained optimized designs. As mentioned the geometries proposed by topology optimization methods are best exploited by additive manufacturing although there remains some limitations to this unique fabrication technique

that need to be addressed in topology optimization algorithms. Some of the problems have been tackled through the past two decades. Topology optimization with material anisotropy was targeted by [1], self-support structure design was discussed by [9]. One of the greatest challenges encountered in manufacturing the structures proposed by topology optimization methods is the overhang angle that needs special treatment during the process of fabrication by additive manufacturing. To overcome this problem, there is a need to discover the best procedure in introducing this constraint within the topology optimization algorithm to achieve better results in terms of manufacturability. We addressed the issue in this research paper by introducing a new algorithm that removes need of so called support structures that are partly used for tackling the overhang problems.

2. Problem definition and context

2.1. Topology optimization: Review

Since the landmark research work by [2, 14] there have been intensive work done by researchers proposing different topology optimization approaches such as element-based approaches (density, topological derivatives, level set, etc.), discrete approaches (evolutionary based algorithms), there also exist gradient based algorithms (optimality criteria, method of moving asymptots) and non-gradient based algorithms (genetic algorithms).

We use the optimality criteria method (OC) for topology optimization, which is one of the most prominent gradient-based mathematical optimization algorithms. This method was used by [14] in a 99-line MATLAB code where he discussed optimizing an MBB (Messerschmitt-Bolkow-Blohm) problem.

In general, optimization algorithms are associated with the Finite Element Method as shown in Figure 1 thus, we follow the same logic in this paper. The following mathematical representation summarizes the topology optimization problem discussed in current work. That is maximizing the global structural static stiffness of a structure. This is equivalent to minimize the compliance (strain energy) :

$$\text{Minimize}: \quad C(X) = \mathbf{U}^T \mathbf{K} \mathbf{U} \quad with \quad X = (\rho_1, \rho_2, \cdots, \rho_n)$$

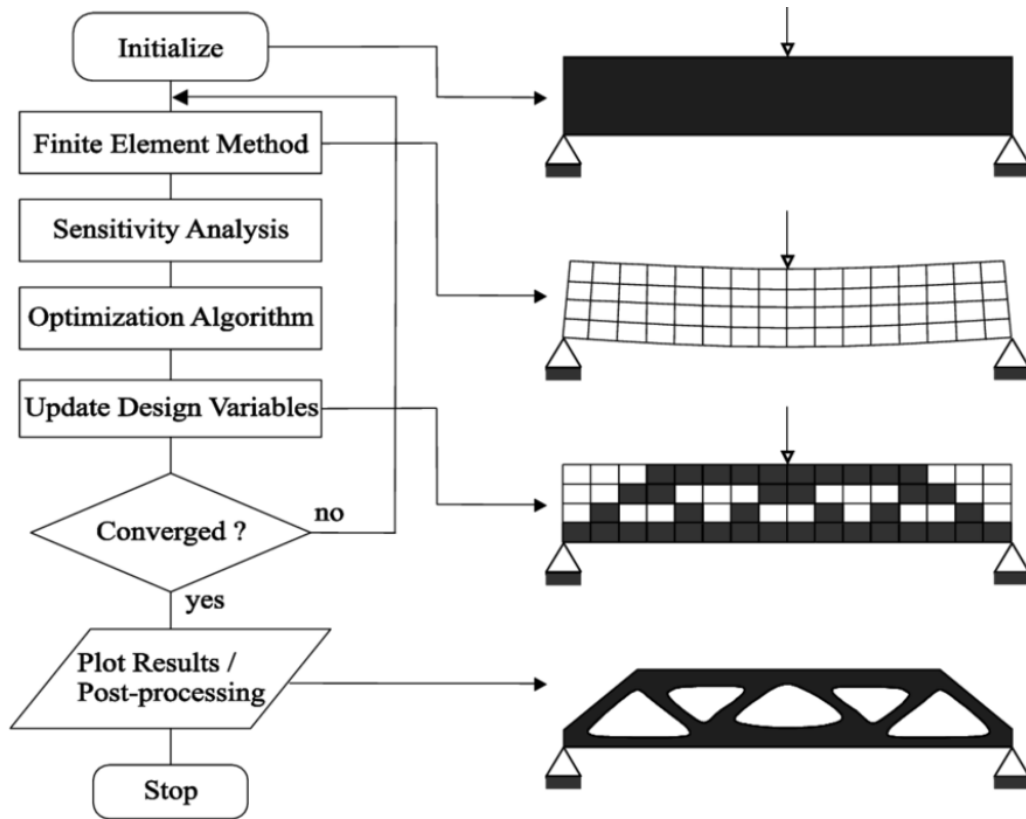$$\text{Subjected to}: \quad \frac{V(X)}{V_0} = f$$

where

Figure 1: FEM based topology optimization procedure. Adapted from [2].

- C is the compliance (objective function),

- $\mathbf{U}$ and $\mathbf{K}$ are the global displacement vector and global stiffness matrix respectively,

- $V(X)$ and V_0 are the material volume and design volume respectively,

- f is the prescribed volume fraction (maximum volume fraction of material remaining),

- X is the vector of design variables (ρ_i is the density of element i).

2.2. AM Contrainst : overhang angle

In most additive manufacturing processes in order to have successfully built overhang components support structures need to be integrated in dif-

ferent stages of the process. The disadvantages of the necessity for support structures is an issue that is an ongoing field of research where solutions to alleviate the negative effects of such structures are being sought. In majority of optimization cases, the proposed model by optimization algorithm tends to form the overhanging structure which technically requires a support structure for production purpose in additive manufacturing. Various researchers proposed different approaches to target this issue. For instance support slimming seeks to minimize the amount of material used in support structures. In an ideal case the reduction of support structures to zero is preferred. In the following section we discuss our proposed algorithm integrated in the optimization iteration that provides the designers to avoid having any support structures at all.

2.3. Proposed approach

To overcome the problem of support structures, there is a need to discover the best procedure in introducing the additive manufacturing constraint within the topology optimization algorithm to achieve better results in terms of manufacturability. The additive manufacturing constraints which are normally validated at the end of the process are now being reordered and put together with other design constraints. The difference between the classical method and the proposed method in this project is that this new method parallelizes the two validations which refer to additive manufacturing constraint and other constraints at the same time for making the topology optimization algorithm more efficient by shortening the time and reduce the overall cost (Figure 2). Our method is an extension of the method introduced by Langelaar. In his method Langelaar [6, 7] included a simplified additive manufacturing process model in the problem formulation, where the overhang angle restriction that applies to the targeted additive manufacturing processes was rigorously enforced at every step of the optimization process. The mechanism functions by means of a layer-wise applied spatial filter, simulating the printing of the part. The novelty of our work is computing the gravity center of each element, once the gravity center of each element is defined the printing layers are defined according to the printing direction. In addition to the mentioned criteria we define a critical angle for each element that sweeps the inferior layer elements in a conical shape. All the elements that are simultaneously included in the immediate inferior layer and whose gravity center is swept by the critical angle cone are considered by the code as the support elements.
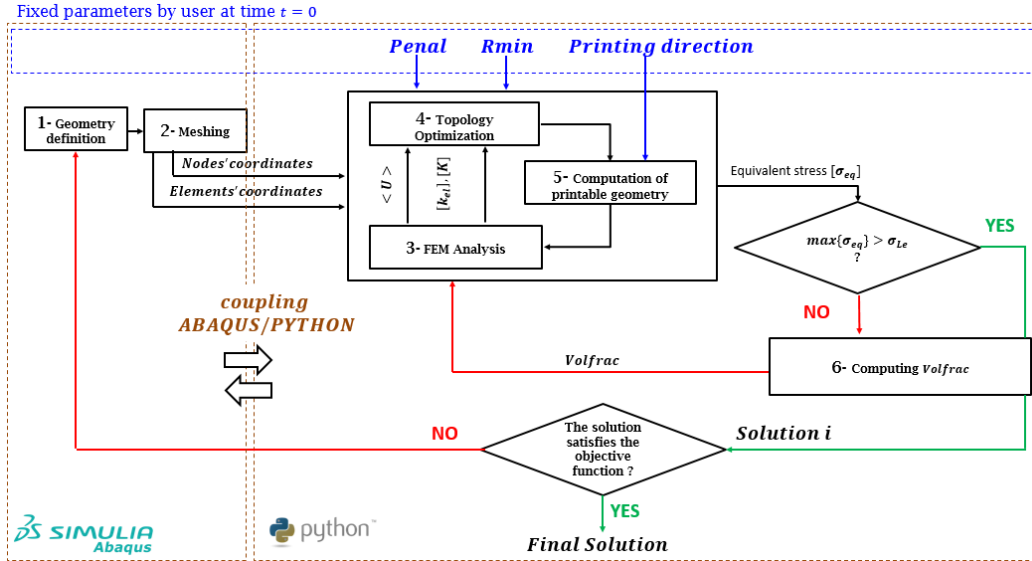
Figure 2: Topology optimization algorithm considering additive manufacturing constraints.

3. Results and Discussion

The results of the topology optimization presented in this paper are obtained using a finite element based topology optimization in house code written in python and interpreted and visualized using ParaView [11], an open-source, multi-platform data analysis and visualization application for interactive, scientific visualization.

Overall our study was carried out considering two main criteria,

- Compliance minimization topology optimization with two targeted volume fractions as constraints: $0.5V_0$ and $0.7V_0$,

- Compliance minimization topology optimization with elastic stress limit constraint.

The Finite Element representation of the model is shown in Figure 3. Our FE model is built using 28449 of C3D8R which is a general purpose linear brick element, with reduced integration (1 integration point). The functional surfaces of the engine are preserved by an offset of $3mm$ which include all

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four counter-bores, two holes on clevis arms and the entirety of the bottom surface as depicted in Figure 4. The loading condition applied to the jet engine bracket is a static linear load of 35.5 KN applied vertically. There is a total of 6 different simulations performed as a combination of different load cases and topology optimization criteria as shown in Table 1.
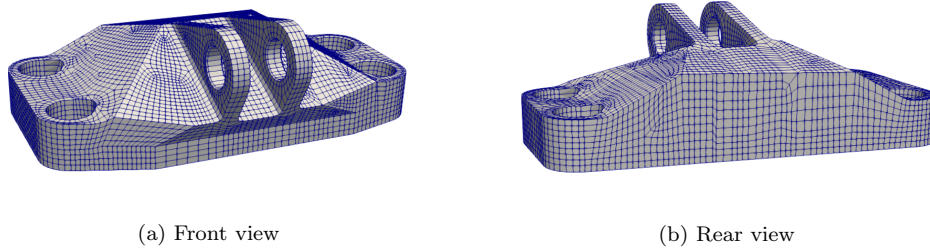

(a) Front view

(b) Rear view

Figure 3: Finite Element rpresentation of the General Electric jet engine bracket.
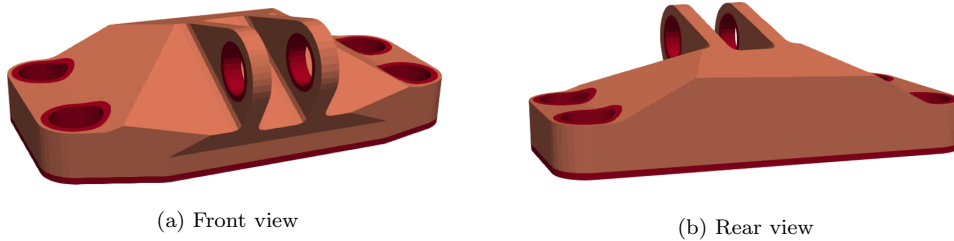

(a) Front view

(b) Rear view

Figure 4: Representation of the functional surfaces on the GE jet engine bracket

Table 1: Six simulations ($S_1 - S_6$) perfoemd considering different TO criteria for two load cases.

TO criteria		Load case $n°$ 1	Load case $n°$ 2
TO with volume fraction constraint	0.5	S_1	S_4
	0.7	S_2	S_5
Elastic stress limit constraint		S_3	S_6

Figure 5 shows the optimized jet engine bracket which is obtained using the load case $n°$ 1 which is a vertical linear static load. The topology optimization criterion considered in the process is $0.5V_0$ volume fraction meaning

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that the final geometry contains only 0.5 of the initial geometry's volume. The final Von Mises stress that the piece undergoes is of 416.5 MPa magnitude.
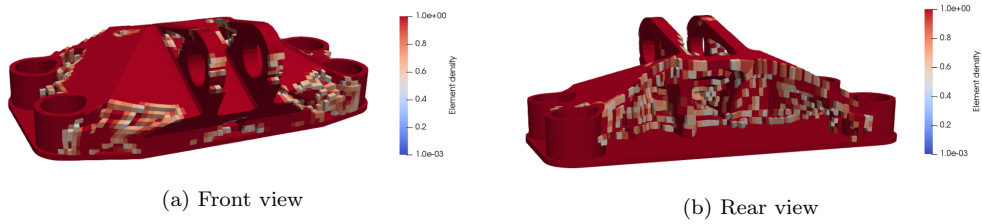

(a) Front view

(b) Rear view

Figure 5: Optimized jet engine bracket with 0.5 of the initial volume remaining

Now considering the volume fraction of 0.7 of the the initial volume as the target we will obtain the optimized geometry as shown in Figure 6. The load case for this optimization is still a vertical linear static load.
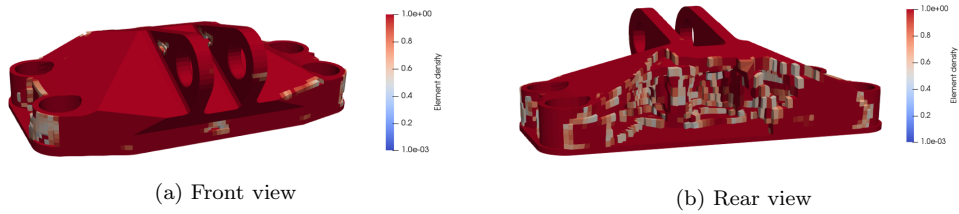

(a) Front view

(b) Rear view

Figure 6: Optimized jet engine bracket with 0.7 of the initial volume remaining

A third type of simulation that we considered in our study is based on a final Von Mises stress threshold. The optimized piece obtained considering such criterion is not necessarily and optimized piece and it maintains 0.98 of its initial volume.
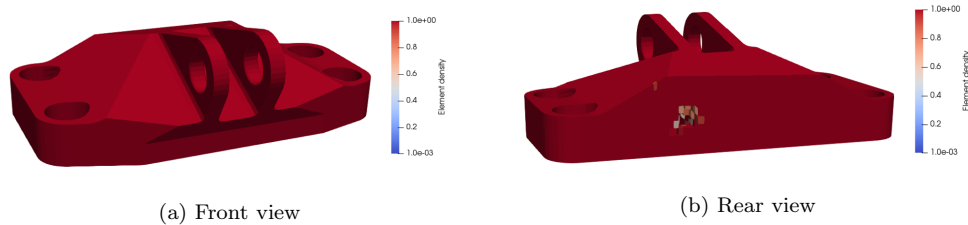
(a) Front view   (b) Rear view

Figure 7: Optimized jet engine bracket considering elastic limit as TO criterion

4. Conclusion

In this study we integrated a new algorithm in to the topology optimization method OC (Optimality Criteria), enabling us to design structures ready for additive manufacturing without having to add support structures. Our algorithm allows us to reduce the structural mass without compromizing the required strength for the respected function for which they are designed. All this is done while respecting a critical angle eliminating the necessity for having support structures which are undesirable from an specifically economic point of view.

We performed our simulations using the jet engine bracket and obtained the computationally satisfying results. From a design point of view the optimized piece doesn't appear to be respecting the norms of an structurally well designed piece, however, at this stage this is not at all the main objective of this study. A final step in order to validate our algorithm would be printing our optimized piece using AM process and verify the printability of the optimized model without needing the support structures.

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